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Photon-induced neutron polarization from the $^2H(\gamma, \vec{n})^1H$ reaction within the NN-force model with an intermediate dibaryon

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A model for the NN force, which is induced by the formation of an intermediate dibaryon dressed with σ- and other meson fields, has been developed by the present authors in previous years. This model is applied to the deuteron photodisintegration processes with the main focus on the γ-induced polarization P'_y of the neutron at energies below $E_\gamma \lesssim 30$ MeV. The inclusion of the intermediate dibaryon leads to a model of the NN force completely different to the conventional NN potential models at short distances. Here the model is tested on the nucleonic level through comparison to rather similar predictions from the conventional NN potential model both for the total and differential cross sections and also for the spin polarization of the ejected neutrons. The predictions of the present model are at least of the same quality than those for the Nijmegen potential; the visible differences with experimental data for P'_y still remain. However, in combination with the previous results a consistent description can be achieved simultaneously for many observables.

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I. MOTIVATION OF THE STUDY

Despite the very long and rich history and huge literature of works performed to date, the problem of electromagnetic (e.-m.) currents in the deuteron can by no means be considered fully resolved. As a good demonstration of the existing problems in this field we quote some recent calculations, e.g., for the γ-induced spin polarization of neutrons emerging from low- and intermediate-energy deuteron photodisintegration [1,2]. There are also ambiguities for the cross section and polarization observables for the closely related $pp \to pp\gamma$ and $pn \to pn\gamma$ bremsstrahlung reactions at $E_p \approx 200$ MeV and other energies [3]. In both processes, quite serious and enigmatic deviations from the data have been found, which cannot be resolved by incorporation of the conventional two-body meson-exchange currents (MEC) and the relativistic corrections. Moreover, these disagreements are found for all calculations with any modern so-called high-accuracy NN-potential models, like the AV18, CD-Bonn, or Nijmegen models. The current situation on the quantitative explanation of the γ-induced neutron polarization in the deuteron photodisintegration looks catastrophic because the two-body MEC contributions increase noticeably even the differences between data and predictions made with only nucleonic currents [1]. This observation is in sharp contrast to the majority of other cases, where the MEC contributions generally improve the agreement with the data reached with the nucleonic currents only. Thus, the root of the problem seems to be deeply hidden in the physics of the NN interaction.

Some time ago, we suggested [4,5] an alternative concept for the short-range NN interaction based on the generation of a six-quark bag in the intermediate state dressed with π-, σ-, and other meson clouds that represent the dressed bag (DB) dibaryon concept. This model can be considered as a further generalization of the early multiquark models (based on the MIT bag [6–8], the resonating group method (RGM) approach [9–11], or the quark chiral models [12–14]), because it unifies both the multiquark components and the meson cloud effects to a single model. Later, the above dibaryon model was formulated [15] in a fully covariant EFT-approach, and some effective relativistic NN potential (nonlocal and energy-dependent) was derived from the relativistic EFT formulation. With the dibaryon model, we could fit easily the lower partial waves of NN interaction for energies ranging from 0 to about 1000 MeV using only a few free basic model parameters [5]. In the following studies [16], the model was applied successfully to explain some long-standing puzzles in the deuteron and in the $3N$ systems, especially the puzzle of the Coulomb displacement energy for the binding energies of ^{3}He and ^{3}H. Also a quantitative description for the electromagnetic structure of deuteron (mainly its magnetic properties and form factors [17,18]) were derived. And at last, very recently the above picture of an intermediate dibaryon in the NN system dressed with σ-, π-, and other meson fields has been confirmed in the series of experimental studies [19–21] for the $\pi^0\pi^0$ production in $p + n \to d + \pi^0\pi^0$ and $p + d \to {}^3\text{He} + \pi^0\pi^0$ (or $\pi^+\pi^-$) collisions in the GeV energy range.

Thus, it is very interesting to apply the above dibaryon model that works well at higher energies to study the γ-induced neutron polarization puzzle in the photodisintegration of the deuteron at low energies where the NN part plays the dominant

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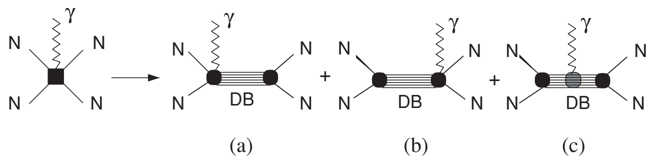

FIG. 1. Schematic representation of the new s-channel "two-body" currents induced by an intermediate dibaryon.

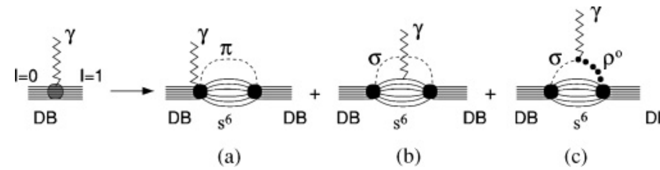

FIG. 2. Contributions to the direct γ-dibaryon interaction [the inner part in Fig. 1(c)]. The bare dibaryon is represented here by the six-quark configuration $|s^6[6]\rangle$.

role. Therefore, the NN sector of the model is being tested here, keeping in mind that the conventional two-body exchange currents are replaced in our case with the respective s-channel dibaryon currents [17].[1] Other important distinctions of the dibaryon model predictions from the conventional approaches are the rather different NN-scattering wave functions, especially for $^1S_0$ and $^3S_1$-$^3D_1$ channels at short ranges. This difference, in turn, leads to quite noticeable deviations of the $M1$-transition matrix elements which play a crucial role in the interference with the $E1$-transition amplitude in the P_y' calculations. Therefore, it is an instructive study to compare the results obtained within our dibaryon model with those of the conventional approaches [1].

II. THE PRESENT STUDY

The complete formalism for the P_y' calculations with nucleonic currents can be found in many articles (see, e.g., Refs. [22–24]), and thus it is omitted here. The detailed formalism for the new s-channel mesonic currents (Fig. 1) was presented in our previous works [17,18] together with their comprehensive tests against the deuteron e.-m. properties. The graphs in Figs. 1(a) and 1(b) represent the s-channel two-body currents generated by the $NN \to DB$ and $DB \to NN$ transitions. The spin part of the dibaryon current will contribute to $M1$-photon absorption at low energies, so that the following magnetic interaction term corresponds to these contact diagrams

$$H_{\rm e.m.}^{\rm DB} = -e_p \mathbf{Q}_{M1}^{\rm DB}\mathbf{H}, \quad \mathbf{Q}_{M1}^{\rm DB} = \sum_{I=0,1} \mathbf{Q}_{M1,I}^{\rm DB}, \tag{1}$$

where

$$\mathbf{Q}_{M1}^{\rm DB}(\mathbf{q}; r, \tilde{r}) = \frac{Z}{2M_N}\left[(\mu_p+\mu_n)\frac{\boldsymbol{\sigma}_p+\boldsymbol{\sigma}_n}{2} + (\mu_p-\mu_n)\frac{\boldsymbol{\sigma}_p-\boldsymbol{\sigma}_n}{2}\right]$$

$$\times\left[\frac{1}{q}j_1(qr/2)\frac{d\varphi_{2S}(r)}{dr}\frac{\lambda(\tilde{E})}{2M_N}\varphi_{2S}(\tilde{r}) + \varphi_{2S}(r)\frac{\lambda(E)}{2M_N}\frac{1}{q}j_1(q\tilde{r}/2)\frac{d\varphi_{2S}(\tilde{r})}{d\tilde{r}}\right]. \tag{2}$$

The contact term in Eqs. (1) and (2) is expressed through the radial derivative of the nonlocal NN potential in the DB model (see Ref. [17] for details)

$$V_{NN}(E; r, \tilde{r}) = \varphi_{2s}(r)\,\lambda(E)\,\varphi_{2s}(\tilde{r}), \qquad \lambda(E) = \lambda(0)\,\frac{E_0+\alpha E}{E_0-E}. \tag{3}$$

In addition, Fig. 1(c) describes the direct interaction of the e.-m. field with the intermediate dibaryon. The leading graphs for such an interaction will include the loops with π, σ, and ρ^0 mesons (see Fig. 2). The bare dibaryon is represented here by the six-quark configuration with symmetry $|s^6[6]\rangle$. All the graphs in Fig. 2 corresponding to the s-channel processes with $\Delta I = 1$ will contribute to the magnetic $M1$ transition in the low-energy $d(\gamma, \vec{n})p$ reaction. It is important here to stress that our new s-channel current is coupled to the dibaryon as a whole and does not really touch with single-quark degrees of freedom—in agreement with common belief about low energies and low momentum transfers.

Although the total contribution of such s-channel two-body currents is expected to be rather small (due to a rather low probability of the intermediate dibaryon) this contribution could still manifest itself in P_y' due to its interference with the large amplitudes coming from the nucleonic currents. Because our main interest in the present work is a detailed comparison of the predictions between dibaryonic and conventional NN force models, first of all on the nucleonic level, we postpone these specific dibaryon contributions to a later publication.

In the present calculation we use the operator of e.-m. interaction $H_{\rm e.m.}$ which is in agreement with the Siegert theorem. In the nonrelativistic long-wave approximation it takes the form (see Ref. [22] for details)

$$H_{\rm e.m.}' = -e_p(\mathbf{Q}_E'\cdot\mathbf{E}' + \mathbf{Q}_M'\cdot\mathbf{H}') + H_{\rm e.m.}^{\rm DB\,\prime}, \tag{4}$$

$$\mathbf{Q}_E' \approx \frac{1}{2}\left[\mathbf{r}' + \frac{(\mathbf{q}'\cdot\mathbf{r}')}{2}\frac{\mathbf{r}'}{2}\right] = \mathbf{Q}_{E1}' + \mathbf{Q}_{E2}', \tag{5}$$

$$\mathbf{Q}_M' = \frac{1}{2m_N}\left[\left(\mu_p+\mu_n-\frac{1}{2}\right)\frac{\boldsymbol{\sigma}_p+\boldsymbol{\sigma}_n}{2} + \frac{1}{2}\mathbf{J}\right]e^{i\mathbf{q}'\cdot\mathbf{r}'/2} + \frac{1}{2m_N}\left[(\mu_p-\mu_n)\frac{\boldsymbol{\sigma}_p-\boldsymbol{\sigma}_n}{2}\right]e^{i\mathbf{q}'\mathbf{r}'/2} \approx \mathbf{Q}_{M1,0}' + \mathbf{Q}_{M1,1}', \tag{6}$$

[1] In our approach the conventional t-channel two-nucleon MEC contributions like $\rho\pi\gamma$, seagull terms, etc., require some special care and essential revision because these contributions should be made to be consistent with the underlying NN interaction model. One should expect, however, that all these conventional contributions will be lower in our case as compared to conventional NN model due to much lower cut-off parameter values $\Lambda_{\pi NN}$, $\Lambda_{\pi N\Delta}$, etc. (these are about 0.5–0.7 GeV in contrast to 1.2–1.5 GeV in conventional MEC models).

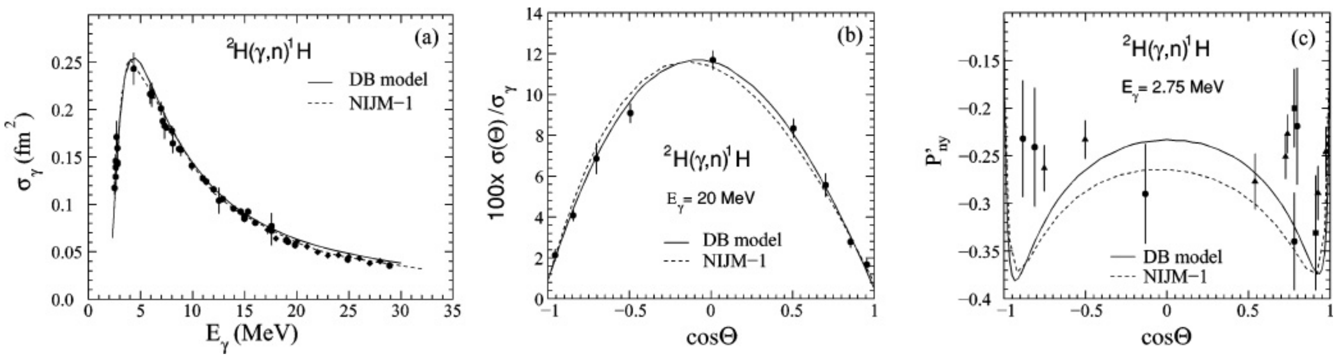

FIG. 3. The predictions for the total cross section of the photodisintegration of the deuteron (left), the differential cross section at $E_\gamma =$ 20 MeV (center), and the angular distribution of neutron polarization P_y at $E_\gamma = 2.75$ MeV (right) are compared to the respective experimental data [25–27]. The Moscow-Tübingen (solid lines) and the Nijmegen-1 [1] (dashed lines) potentials were employed.

where $\mathbf{J} = \mathbf{L} + (\boldsymbol{\sigma}_p + \boldsymbol{\sigma}_n)/2$. Here (θ', φ', r') are spherical coordinates of the interaction point $\mathbf{r}'$ defined in the $X'Y'Z'$ frame where the Y' axis is directed normally to the reaction plane $\hat{\mathbf{Y}}' = \mathbf{q} \times \mathbf{p}/|\mathbf{q} \times \mathbf{p}|$ defined by the photon momentum $\mathbf{q}$ and the relative momentum $\mathbf{p} = (\mathbf{p}_p - \mathbf{p}_n)/2$ of the outgoing state of the np system (this is a rotating frame with $\hat{\mathbf{Z}}' = \hat{\mathbf{p}}$). The incident photon is quantized in the laboratory frame XYZ with the Z axis directed along the momentum $\mathbf{q}$. Here and below, each variable quantized in the rotated frame $X'Y'Z'$ is denoted by a prime.

The spin polarization of the ejected neutron is defined by the ratio:

$$P'_{ny}(\Theta) = \frac{1}{3} \sum_{MM'_J\bar{M}'_J} \frac{1}{\bar{\sigma}(\Theta)} \times \int_0^{2\pi} \frac{d\Phi}{2\pi} \big\langle \Psi_{M\bar{M}'_J}(\Theta,\Phi) \big| \sigma^{(n)}_{y'} \big| \Psi_{MM'_J}(\Theta,\Phi) \big\rangle. \quad (7)$$

where $\sigma^{(n)}_{y'}$ is the neutron spin operator quantized along the Y' axis and $\bar{\sigma}(\Theta)$ is the total neutron yield at the polar angle Θ:

$$\bar{\sigma}(\Theta) = \frac{1}{3} \sum_{MM'_J} \int_0^{2\pi} \frac{d\Phi}{2\pi} \langle \Psi_{MM'_J}(\Theta,\Phi) | \Psi_{MM'_J}(\Theta,\Phi) \rangle. \quad (8)$$

The wave function $\Psi_{MM'_J}(\Theta, \Phi)$ defined in Ref. [22] describes the spin state of the np system generated by the linearly polarized photons and polarized deuterons taken as the incident particles. The values Θ, Φ, and M characterize the incident-particle polarization states: the photon electric vector $\mathbf{E}$ is directed along the angle Φ with respect to the Y axis and M is the projection of the deuteron angular momentum onto the Z axis directed along the photon beam. However, the above definition of P'_y, which includes the summation over M and averaging over the azimuthal angle Φ, implies that the P'_y values correspond to experimental data obtained with a nonpolarized beam and a nonpolarized target. With fixed values Θ, Φ, and M the wave function $\Psi_{MM'_J}(\Theta, \Phi)$ depends only on a single independent variable M'_J, which is the projection of the total angular momentum of the final pn system onto the Z' axis.

The wave function $\Psi_{MM'_J}(\Theta, \Phi)$ can be calculated through matrix elements $\langle f | H'_{\text{e.m.}} | i \rangle$ of the electromagnetic-interaction Hamiltonian with $|f\rangle$ taken as the final np-scattering state satisfying the incoming-wave boundary condition.

III. A SHORT DISCUSSION OF THE RESULTS

The total cross section for the deuteron photodisintegration as a function of photon energy E_γ is displayed in Fig. 3(a) up to 30 MeV in comparison with experimental data of many groups [25]. Here the predictions of the dibaryon model shown by solid lines are compared also to the results obtained with the conventional NN interaction models and respective two-body current contributions [1] (dashed curves). It is seen that in general the DB model leads to similar agreement for the total photoabsorption cross section as compared to the conventional models [1]. The small overestimation of the data on the level 3% is assumed to be healed when the interference terms with the full dibaryon current will be included.

In Fig. 3(b) the angular dependence of the photodisintegration cross section is shown at $E_\gamma = 20$ MeV and confronted with the respective experimental data [26] and also with the results of previous calculations [1] performed with a conventional NN potential. It is evident that the DB-model description of the unpolarized cross sections compares well with the Nijmegen model.

Let us turn now to the γ-induced neutron polarization. In Fig. 3(c) the angular dependence of the P'_y at a very low photon energy of $E_\gamma = 2.75$ MeV is displayed and compared to the conventional model predictions and to the respective experimental data [27]. Here, both approaches do not agree well with the data at forward and backward angles. However, the data have large uncertainties and exhibit large scattering.

In Fig. 4 the results of our calculation for P'_y at 45° [Fig. 4(a)], 90° [Fig. 4(b)], and 135° [Fig. 4(c)] are compared to the data [28] and to the theoretical results of Ref. [1]. Here, the pure nucleonic results are shown for the dibaryon model (solid lines) and the Nijmegen model [1] (long dashed lines). It is evident from Fig. 4(a) that the predictions for the two models are in reasonable agreement with the data up to $E_\gamma \approx 15$ MeV but they deviate from the data at higher photon energies.

Adding the dibaryon-induced meson-exchange currents to the nucleonic current destructively ($NN - DB$) or constructively ($NN + DB$) leads to a relatively small band given by the hatched areas in Fig. 4. In contrast to this, the inclusion of

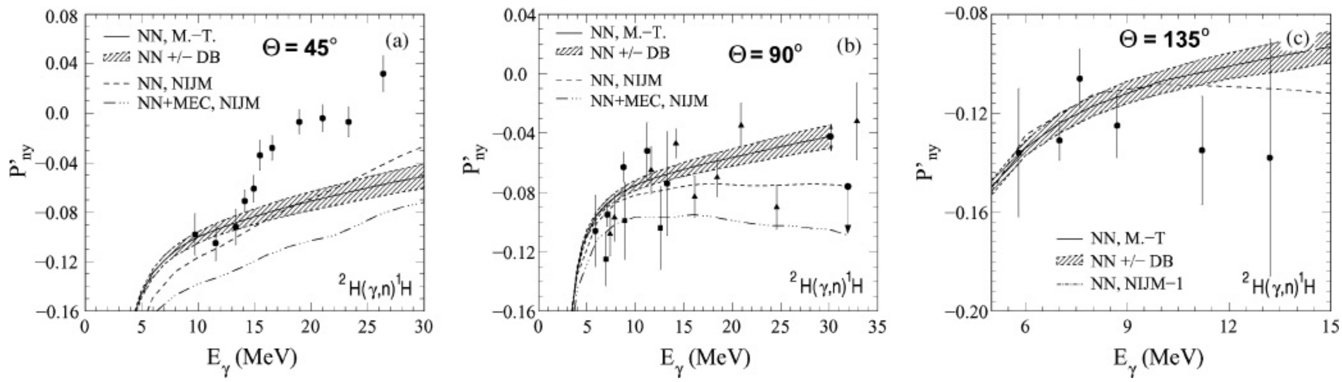

FIG. 4. The γ-induced polarization P_y' of the neutron measured in the $^2\text{H}(\gamma, \vec{n})^1\text{H}$ reaction at polar angles of $\Theta = 45^\circ$ (left), $\Theta = 90^\circ$ (center), and $\Theta = 135^\circ$ (right) in comparison to the predictions. The same notions as in Fig. 3 is used. The results for the dressed bag model in case of destructive ($NN - DB$) or constructive ($NN + DB$) interference between the NN and DB (two-body) currents are shown by the short-dashed lines encompassing the hatched area, respectively. For comparison, the results for the full Nijmegen (NIJM) model with the conventional two-body current (denoted as MEC) and the relativistic corrections are shown by dash-dotted lines and the Nijmegen nonrelativistic NN model is represented by long-dashed lines (adapted from Ref. [1]). The data are from Ref. [28].

the traditional (t-channel) MEC contribution to the Nijmegen NN model prediction (dash-dotted line) destroys even the exemplary agreement with the data. The same conclusion can be drawn also for the other angles, $\Theta = 90^\circ$ [Fig. 4(b)] and $\Theta = 135^\circ$ [Fig. 4(c)], although the experimental data here are spread widely.

In fact, we used in the present study the same s-channel current as previously [17], where this new current was essential to explain quantitatively the magnetic characteristics of the deuteron and also the circular polarization, P_γ, of the photons in the thermal neutron capture reaction $\vec{n} + p \to d + \vec{\gamma}$. In the present deuteron photodisintegration study at energies in the range of 2–30 MeV, the contribution of the above dibaryon current is rather small [hatched areas in Figs. 4(a), 4(b) and 4(c)]. The unimportance of this s-channel current in the present process can be explained by the fact that it contributes to the $M1$ transition, whereas the main transition component at the low energies $E_\gamma \sim 2 \div 30$ MeV is of electric dipole ($E1$) nature. It is observed in Fig. 4 that the two-body DB current contributions do not modify noticeably the predictions found with the nucleonic currents, in contrast to the potential NN models with the conventional two-body currents [dash-dotted lines in Figs. 4(a) and 4(b)].

Concerning the two-body current effects, another important distinction of the DB model from the conventional one arises from the fact that the γ quantum, when interacting with the intermediate dressed bag as a whole [Figs. 2(a) and 2(c)], can rotate its total spin without affecting the inner quark spin, i.e., without quark spin rearrangement. The latter can be related to rather high excitation of the bag and has no importance at low energies. Such current terms should give a noticeable contribution to P_y'.

Summarizing the presented results one can conclude that the DB model for the intermediate- and short-range NN interaction leads to predictions for the photon-induced neutron spin polarization for the $d(\gamma, \vec{n})$ on the nucleonic level, which are at least of the same quality as those found with the Nijmegen potential models. This is an extremely interesting result in view of the fact that the structure of the DB-interaction potential is strongly deviating from the conventional one. In particular, at short distances the DB model [5] leads to a highly nonlocal and energy-dependent potential in the NN sector. However, we can expect some additional contributions to P_y' from other dibaryon currents related to π-meson loop in the dibaryon (which will contribute to the dipole transitions). Thus, combining both the previous results [17,18] for several important e.-m. NN observables with those of the present work on the $d(\gamma, \vec{\text{n}})$ reaction one can conclude that the general description of the deuteron e.-m. observables with the DB model at low- and even high momentum transfer has an advantage in general over those given by the conventional force models. Nevertheless, more detailed and comprehensive studies of the DB model are still needed.

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